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DOI:10.1088/1742-6596/409/1/012075

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2013 J. Phys.: Conf. Ser. 409 012075

(http://iopscience.iop.org/1742-6596/409/1/012075)

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Abstract. LOPES is a digital antenna array for the radio measurement of cosmic-ray air showers at energies around 10^{17} eV. It is triggered by the KASCADE-Grande air-shower array at the Karlsruhe Institute of Technology (KIT), Germany. Because of an absolute amplitude calibration and a sophisticated data analysis, LOPES can test models for the radio emission to an up-to-now unachieved level, thus improving our understanding of the radio emission mechanisms. Recent REAS simulations of the air-shower radio emission come closer to the measurements than any previously tested simulations. We have determined the radio-reconstruction precision of interesting air-shower parameters by comparing LOPES reconstructions to both REAS simulations and KASCADE-Grande measurements, and present our latest results for the angular resolution, the energy and the X_{max} reconstruction based on the radio measurement of about 500 air showers. Although the precision of LOPES is limited by the high level of anthropogenic noise at KIT, it opens a promising perspective for next-generation radio arrays in regions with a lower ambient noise level.

1. Introduction

The radio detection of cosmic-ray air showers is under investigation since almost 50 years [1], [2]. Reconstructing air-shower parameters, like the energy and the atmospheric depth of the shower maximum, $X_{\max}$, turned out to be much more challenging than expected. First, a sufficient understanding of the radio emission is necessary, which requires detailed simulations taking into account not only the dominant geo-magnetic emission process [3], [4], but also the sub-dominant Askaryan effect[1] [5], and the effect of the refractive index of air [6], [7], which affects the coherence conditions for the radio emission. Second, natural and especially human-made radio background strongly affects the radio measurements and leads to a relatively high detection threshold around $10^{16} - 10^{17}$ eV. Still, research on the radio technique continues, since it offers a duty cycle close to 100 %, which allows to increase the effective observing time by an order of magnitude compared to the established air-fluorescence and air-Cherenkov techniques.

LOPES [8], [9] is a digital radio-antenna array triggered by the co-located KASCADE-Grande experiment [10], [11] at the Karlsruhe Institute of Technology (KIT), Germany. Different antenna configurations and orientations have been used to study the polarization of the radio signal [12], [13], which is consistent with a dominant geo-magnetic origin. The results presented here, have been obtained with east-west aligned antennas within an effective bandwidth of $43 - 74$ MHz. To identify the air-shower radio pulses in the noisy environment of KIT, the individual LOPES antennas are digitally combined to an interferometer using an open-source analysis software [14]. Moreover, several steps of data conditioning improve the signal-to-noise ratio, and raw data are corrected for the phase and amplitude behavior of the LOPES hardware, which has been determined in separate calibration measurements [15], [16]. More details on the setup and the analysis procedures can be found in references [17], [9].

2. Results

The usability of the radio technique for ultra-high energy cosmic ray physics depends on reconstruction uncertainties of the important air-shower parameters, i.e. the arrival direction, the energy of the primary particle, and the atmospheric depth of the shower maximum, $X_{\max}$, which is correlated with the primary mass. In principle, this precision can be estimated with simulations, but although the theoretical understanding of air-showers and their radio emission has dramatically improved in recent years, it still has deficiencies. REAS3 [18], a Monte-Carlo simulation code taken into account both the geo-magnetic radio emission as well as the Askaryan effect, can reproduce the amplitude of LOPES events within the measurement uncertainties, but produces too steep lateral distributions [19], [20]. This might be related to the refractive index now implemented in REAS (v3.11) currently under investigation. Thus, we have determined the radio-reconstruction precision experimentally, by comparing the LOPES reconstruction to KASCADE-Grande, respectively KASCADE, reconstructions of the same events (figure 1).

2.1. Arrival direction

The arrival direction is reconstructed by LOPES with cross-correlation beamforming [21]. A fit using the KASCADE-Grande direction as input determines the direction by maximizing the cross-correlation amplitude. The KASCADE-Grande angular resolution is negligible against the demonstrated upper limit of the LOPES angular resolution of about 0.7°. A potential bias of the KASCADE-Grande input direction to the results has been studied and can be neglected as well [22]. Furthermore, we observe a slightly better angular resolution when using a conical wavefront for the beamforming instead of a spherical wavefront, which supports our recent result that the radio wavefront is approximately conical [23].

[1] Askaryan effect = radio emission due to the net charge variation during the shower development

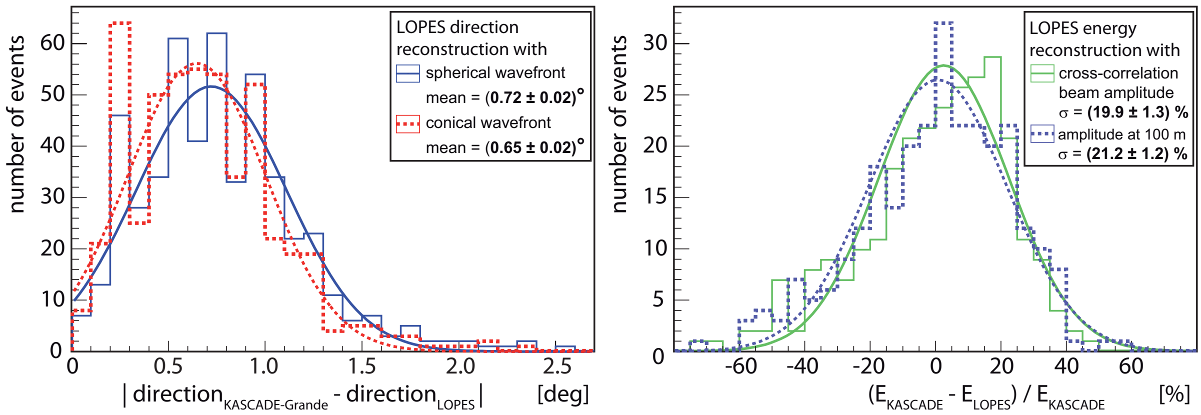

Figure 1. Comparision of the KASCADE-Grande and LOPES direction reconstructions (left) and energy reconstructions (right). All stated numbers are determined with Gaussian fits.

2.2. Energy

Theoretically an energy precision as good as a few percent might be possible [24], but in a real experiment noise and calibration uncertainties limit the achievable precision to $5 - 10\,\%$. In addition, there are systematic uncertainties on the absolute energy scale, especially due to our limited knowledge of air-showers physics. The energy of the primary particle has been reconstructed with LOPES by two different methods: First, using the amplitude of the cross-correlation beam after correction for the distance to the shower axis by assuming an exponentially-decreasing lateral distribution [25]. Second, interpolating the individually measured lateral distributions to a typical axis distance. Since this specific distance has only little impact on the results shown here, we have used 100 m for all events (a more sophisticated variant of this method takes into account that the optimal distance depends slightly on the shower inclination [26]). For both methods, we correct the amplitude for the geo-magnetic effect dividing by the east-west projection of the Lorentz-force vector, which implies a correction on the azimuth and zenith angle. We do not observe an improvement of the energy reconstruction by applying an additional correction for the shower inclination as proposed by Allan [2]. Such an additional correction might only be adequate when the amplitude is measured at larger distances, since the slope of the lateral distribution depends on the zenith angle [27]. We have cross-calibrated the LOPES energy scale with the KASCADE energy, i.e. centering the energy distributions (figure 1, right) around 0. The width of the distributions is about 20 % for both reconstruction methods and seems to be dominated by the KASCADE energy uncertainty, which allows us to set an upper limit for the LOPES energy precision of about 20 %.

2.3. Atmospheric depth of the shower maximum $X_{\max}$

The sensitivity of radio measurements to the longitudinal shower development has recently been confirmed experimentally [28]: the slope of LOPES lateral distributions is correlated with muon measurements of the KASCADE-Grande muon-tracking detector [29], which are already known to be sensitive to the shower development. The results support the theoretical expectation that the radio signal is primarily sensitive to the geometrical distance between the radio array and the shower maximum, which implies a sensitivity to $X_{\max}$. We have estimated the LOPES $X_{\max}$ precision from the observed correlation to about $115\,\mathrm{g/cm^2}$. Moreover, we have reconstructed $X_{\max}$ for LOPES measurements in two different ways using REAS3 simulations for calibration. Reconstructing $X_{\max}$ with the slope of the lateral distribution yields a precision of about $100\,\mathrm{g/cm^2}$ [30], reconstructing $X_{\max}$ via the cone angle of the radio wavefront results in a precision of about $200\,\mathrm{g/cm}^2$ [23]. In both cases, the LOPES reconstruction seems to be limited by the high level of ambient radio background at KIT, but REAS3 simulations indicate that in low-background environments a precision of at least $30\,\mathrm{g/cm}^2$ is feasible.

3. Conclusion

By comparing LOPES and KASCADE-Grande measurements of the same air-showers, we experimentally estimated the reconstruction precisions of LOPES radio measurements: 0.7° for the arrival direction, an upper limit of $20\,\%$ for the energy, and $115\,\mathrm{g/cm}^2$ for X_{max}. Since LOPES suffers from a high level of anthropogenic radio background, next-generation radio arrays in regions with lower background, like AERA [31] and Tunka-Rex [32], are expected to achieve a significantly better precision. Moreover, these experiments allow to cross-calibrate the radio reconstruction of the energy and of X_{max} with the precise air-fluorescence, respectively air-Cherenkov technique, and thus can test whether the radio precision can finally compete with the established methods.

Acknowledgement

LOPES and KASCADE-Grande have been supported by the German Federal Ministry of Education and Research. KASCADE-Grande is partly supported by the MIUR and INAF of Italy, the Polish Ministry of Science and Higher Education and by the Romanian Authority for Scientific Research UEFISCDI (PNII-IDEI grant 271/2011). This research has been supported by grant number VH-NG-413 of the Helmholtz Association.

References

[1] Jelley J V, Fruin J H, Porter N A *et al.* 1965 *Nature* **205** 327–328
[2] Allan H R 1971 *Progress in Elementary Particle and Cosmic Ray Physics* **10** 171–302
[3] Kahn F D and Lerche I 1966 *Proc. of the Royal Soc. of London A* vol 289 p 206
[4] Ardouin D *et al* - CODALEMA Collaboration 2009 *Astroparticle Physics* **31** 192 – 200
[5] Askaryan G A 1962 *Soviet Physics JETP* **14** 441
[6] de Vries K D, van den Berg A M, Scholten O and Werner K 2011 *PRL* **107**(6) 061101
[7] Ludwig M and Huege T 2011 *Proc. of the 32nd ICRC, Beijing, China* vol 2 #0149
[8] Falcke H *et al* - LOPES Collaboration 2005 *Nature* **435** 313–316
[9] Huege T *et al* - LOPES Collaboration 2012 *Nucl. Instr. and Meth. A* vol 662, Supp. 1 pp S72–S79
[10] Antoni T *et al* - KASCADE Collaboration 2003 *Nucl. Instr. and Meth. A* **513** 490–510
[11] Apel W D *et al* - KASCADE-Grande Collaboration 2010 *Nucl. Instr. and Meth. A* **620** 202–216
[12] Isar P G *et al* - LOPES Collaboration 2009 *Nucl. Instr. and Meth. A* vol 604, Supp. 1 pp S81–S84
[13] Huber D *et al* - LOPES Collaboration 2011 *Proc. of the 32nd ICRC, Beijing, China* vol 3 #0321
[14] Cosmic Ray Tools http://usg.lofar.org/svn/code/branches/cr-tools-stable
[15] Nehls S, Hakenjos A, Arts M J *et al.* 2008 *Nucl. Instr. and Meth. A* **589** 350 – 361
[16] Schröder F G, Asch T, Bähren L *et al.* 2010 *Nucl. Instr. and Meth. A* **615** 277 – 284
[17] Horneffer A 2006 PhD Thesis URL `http://nbn-resolving.de/urn:nbn:de:hbz:5N-07819`
[18] Ludwig M and Huege T 2011 *Astroparticle Physics* **34** 438–446
[19] Schröder F G 2011 PhD Thesis URL `digbib.ubka.uni-karlsruhe.de/volltexte/1000022313`
[20] Ludwig M 2011 PhD Thesis URL `digbib.ubka.uni-karlsruhe.de/volltexte/1000023592`
[21] Nigl A *et al* - LOPES Collaboration 2008 *Astronomy & Astrophysics* **487** 781–788
[22] We thank Johanna Lapp for her work on the LOPES direction reconstruction during her bachelor thesis.
[23] Schröder F G *et al* - LOPES Collaboration 2011 *Proc. of the 32nd ICRC, Beijing, China* vol 3 #0313
[24] Huege T, Ulrich R and Engel R 2008 *Astroparticle Physics* **30** 96–104
[25] Horneffer A *et al* - LOPES Collaboration 2007 *Proc. of the 30th ICRC, Merida, Mexico* vol 4 pp 83–86
[26] Palmieri N (under preparation) PhD Thesis
[27] Apel W D *et al* - LOPES Collaboration 2010 *Astroparticle Physics* **32** 294–303
[28] Apel W D *et al* - LOPES Collaboration 2012 *Phys. Rev. D* **85** 071101(R)
[29] Doll P, Bartl W, Büttner C, Daumiller K *et al.* 2002 *Nucl. Instr. and Meth. A* **488** 517–535
[30] Palmieri N *et al* - LOPES Collaboration 2011 *Proc. of the 32nd ICRC, Beijing, China* vol 3 #0309
[31] Fuchs B for the Pierre Auger Observatory 2012 *Nucl. Instr. and Meth. A* DOI:10.1016/j.nima.2012.01.058
[32] Berezhnev S F *et al* - Tunka Collaboration 2011 *Nucl. Instr. and Meth. A* DOI:10.1016/j.nima.2011.12.091